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Partial Discharge Trends in Medium Voltage Cables measured while in-service with PDOL

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Abstract-- This paper presents partial discharge trends of various developing faults such as drying out of impregnated paper cables, moisture ingress, earth screen damage, etc. These trends were measured over either weeks, or months, by PD-OL (PD Online with Location), which measures and locates PD activity. The presented cases are results from continuous measurements on more than 150 cable connections.

The paper also briefly discusses the principles behind the measurement technique, the centralized data processing, and the internet portal. PD-OL is a mature and unique diagnostic and monitoring tool for medium-voltage power cable connections, up to several kilometers length for any desired period of time (hours, weeks, years). The network owner can monitor the actual health of their cable systems via the internet, backed up by a warning service.

The results show that PD-OL is an economical and reliable alternative for off-line PD measurement methods, while offering so much more.

Index Terms-- Power cable testing, Partial discharges, Diagnostic expert systems, Automatic test equipment, Power cable insulation, Insulation life, Life estimation, Time domain reflectometry, Remote sensing, Fault location

I. INTRODUCTION

PARTIAL discharges are symptomatic of many degradation phenomena in power cables. However, partial discharge show erratic behavior. Their prevalence, and absence depend on electrical and physical conditions. Depending on the measurement method, partial discharges present during normal operation may not be visible during the test, yielding a false negative, or partial discharges present during the test may not be present during normal operation of the cable, yielding a false positive. The best testing condition to measure partial discharges is during normal operation of the power cable. Trending becomes possible when measuring hourly over a prolonged period of time (weeks or months).

The online partial discharge measuring and location system, the PD-OL system, fills the gap of equipment of continuously monitoring in-service medium voltage cable systems. The system consists of three components. The decentralized measurement set measures the partial discharges in the cable. The central data server collects and processes the

measurements received via a secure internet connection. The secure internet portal lets network owners and KEMA specialists review the detected partial discharges. The detected partial discharges show the level and location of degrading accessories or cable sections. Experience shows that the PD-OL system has matured to detect weak points with normally enough time for replacement before a spontaneous failure occurs.

The PD-OL system sensitivity matches the sensitivity of off-line measurement equipment. The PD-OL measurement units are suitable for all types of medium voltage (≤ 42 kV) cable connections. The system works for PILC cables up to 4 km, and for XLPE cables up to 8 km, including all types of accessories installed. One PD-OL measurement set can monitor multiple cable circuits, connected through multiple RMU's or substations, see circuit B below for an example. The measurement units can be installed on the cable connection without taking the cable out of service (depending of safety regulations).

This first half of the paper briefly describes the measurement system, based on the patented [5] test methodology developed by [1], and [2]. This description is similar to the papers presented at the CEPSE in 2008 [6], and CIREP in 2009 [7]. The second half of the paper presents an update of the practical field experience with over 150 measured cable connections over the past 3 years.

II. PD-OL MEASUREMENT SYSTEM

A PD-OL measurement set consists of two individual PD-OL measurement units, one installed at each end of the cable connection to be monitored, in either a substation or a RMU (Ring Main Unit). See for an illustration Fig. 1.

Each measurement unit consists of a sensor/injector unit (PD-OL - SIU) and a control unit (PD-OL - CU). The SIU contains both a sensor, to measure pulses from the cable, and an injector, to inject pulses into the cable. The injected pulses are used for synchronization, local impedance measurements and on-line TDR. The SIU can be separated for easy installation. It is clamped around the cable termination or cable earth connection. This can all be done while the cable remains in-service. An optical fiber link connects the SIU and the CU.

The control unit (the CU) is a small dedicated computer which controls the measurement sequence, the data collection, the signal processing, and the communication. The on board communication facilities (LAN, modem or mobile phone /

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GPRS card) upload the resulting data via the internet to the Control Center at KEMA for further interpretation. Furthermore, the PD-OL units can be reached via the internet for diagnostic purposes and updates. All is performed automatically and remotely, so once installed no physical access to the units is needed.

Fig. 1. PD-OL installation, with at each cable end a control unit (PD-OL - CU) for signal processing and communication via internet and a sensor/injector unit (PD-OL - SIU) for the actual measurement and pulse injection.

III. PD-OL MEASURING SEQUENCE

When a weak spot in a cable produces partial discharges, the cable itself acts as a wave guide for the high frequency signals. At the PD origin, the PD pulse will split in two, each half traveling in an opposing direction. The PD-OL - SIUs, one located at each end of the cable circuit detects the PD pulse and its arrival time, see fig. 2. In order to discriminate PDs from the cable under test from other pulses and to locate their origin, it is necessary to synchronize the measurement time of the two sensors. By injecting and detecting a known pulse at both ends the clocks of the units are synchronized, and the cable propagation time is measured. The patented solution [5] allows both high frequency measurements as well as pulse injection without galvanic contact to the high voltage.

Since the propagation time of the cable is measured on-line and thus is known, accurate time synchronized measurements by the two PD-OL units has become possible. Advanced signal processing techniques ensure this method achieves sufficient reliability and accuracy.

The measurement sequence results in time-synchronized records of data. The control unit uses matched filter banks to judge whether the measured data contains PDs [8]. The resulting tables of detected (PD) pulses from both cable ends are sent over a secure internet connection to the Control Center at KEMA. The Control Center combines the results from both cable ends, which leads to either the elimination of the (PD) pulses from other sources or the determination PD charge and location.

Technical details of the PD-OL measuring system, such as the type of sensors applied, optimal sensor locations, sensor calibration and noise suppression, are also discussed extensively in [1], [2], and [4], including references to more in depth publications on these subjects.

Fig. 2. A weak spot in a cable produces partial discharges measured and recorded by the two PDOL measurement units. The location of the PD is calculated from the difference in travel time of the PD pulse to each sensor.

IV. PARTIAL DISCHARGE TRENDS

Partial discharges depend on the electric field, temperature, and pressure in the insulation medium. In power cables, these factors depend on among others, the operating voltage, heating due to load current, temperature of the soil, previous discharges, etc. All these factors vary in time.

PD-OL has measured over 150 in-service cable connections over several months, some even over one or two years. Since 2007 several interesting incipient failures have been detected. These weak spots have been removed from service before a spontaneous failure had occurred. The partial discharge trends of 6 cases are presented below. These cases include two hot joint connectors, a tree root strangling a PILC cable, excessive fault currents burning the outer sheath of an XLPE cable, and a fluid filled joint. All these cases show distinctly different trends.

A. Circuit A: Hot joint connector

Circuit A contained a joint with a crimp connector at 1678 m in an XLPE insulated cable circuit of 4258 m long. fig. 3 shows the 3D graph of 20 days of measurements on this circuit. The concentrated PDs originate from the joint that failed.

Fig. 3. 3D graph of developing PDs in a failed joint with a crimped connector running hot at 1678 m in circuit A.

The first PDs were visible on 4 August. Over a period of 3 weeks the PDs disappeared and reappeared. The PD origin was very narrow. The network owner was correctly, and timely warned with a recommendation to replace the joint.

The joint was left in the circuit and ran to failure.

B. Circuit B: Hot joint connector

The joint of interest in Circuit B is a joint with a crimp connector at 3526 m in a circuit of 5661 m long. The circuit consists of 4 cable connections, with 3 substations.

As in circuit A the PD origin was very narrow, which is characteristic of a solid joint, see fig. 4. The network owner was correctly, and timely recommended to replace the joint. The joint was replaced on time, avoiding an unscheduled outage. The investigation showed that the joint body had burned from excessive heat of a bad crimp connector, see fig. 5.

Fig. 4. 3D graph of developing PDs in a joint with a crimped connector running hot at 3526 m in circuit B. Circuit B contains 4 cable systems and 3 RMU's.

Fig. 5. The burnt joint body due to excessive heat from the hot crimp connector in circuit B.

C. Circuit C: Tree root damage PILC cable

The weak spot of interest in Circuit C is a piece of cable at 44 m in a cable system of 247 m long. The partial discharges, shown in fig 6., intensified in charge, and frequency.

In comparison to circuit A and circuit B, the PDs originated from a wider area. This is characteristic for impregnated insulation which is degrading by moisture. The PDs are most intense at the location where the insulation has been affected most by moisture. The network owner was recommended to investigate the weak spot. They found a tree root strangling the cable, deforming it such that the lead cover had lifted off the paper insulation, see fig 6, top-right corner,

and providing a spot for moisture to enter the cable.

Fig 6. 3D graph of developing PDs in a paper impregnated cable, due to moisture ingress and voids between lead cover and paper insulation. The graph displays measurements in circuit C covering 102 days. Top-right: A tree root damaged the impregnated paper cable by strangling it.

D. Circuit D: Dried out oil filled termination

The accessory of interest in circuit D is a dried out oil filled terminator at 0 m in a 367 m long cable. The PD frequency was relatively low, but the intensity was high, up to 5,500 pC, see fig. 7. After the oil level in the termination was topped up, the PDs disappeared.

Fig. 7. 3D graph of developing PDs in a paper impregnated cable, due to moisture ingress and voids between lead cover and paper insulation. The graph displays measurements in circuit C covering 102 days.

E. Circuit E: XLPE cable degraded earth screen

The weak spots of interest are sections of XLPE cable at approximately 500 m, 4500 m, and 5000 m in a cable of 7058 m length. Fig. 8 shows the discharges at 5000 m. The PDs were recorded over a period of almost one month. This was a curious observation as the PD origin was far away from the joint locations. The network owner inspected the cable at these PD sites and discovered that the earth wire screen of the XLPE cable was burned away over long lengths, due to excessive fault currents in the copper wire earth screen, see fig. 9.

Fig. 8. 3D graph of PDs measured during almost 1 month on circuit E with clear PDs from a joint that failed. Only PDs from the location near 5000 m are plotted.

Fig. 9. The copper wire earth screen of the XLPE insulated cable of circuit E, was burned away due to excessive fault currents. These spots were found and located with the PD-OL measuring system.

F. Circuit F: Fluid filled joint

The PDs of interest originated from two fluid filled joints at 993 m and 995 m in a PILC cable of 1801 m long, see fig 10. The first set of PDs were visible on 28-12-2009. The PDs disappeared and reappeared five times for a month. From 28-2-2009 the PDs reappeared much stronger at 1400 pC, and during the next two weeks intensified and increased to 2000 pC. The location of the PDs was close to the two fluid filled joints. The joints were replaced and examined. The grease in the joints contained traces electrical treeing, and signs of possible moisture ingress, see fig. 11.

Fig. 10. 3D graph of PDs measured during almost 2 months on circuit F with clear PDs from two fluid filled joints at 993 m and 995 m. Circuit F contains 2 cable systems and 1 RMU at 750 m.

Fig. 11. Fluid filled joint from circuit E containing electrical tracking marks (left) and probably moisture ingress.

V. SUMMARY

The discharge frequency (number of discharge per second), and density vary significantly on the type of developing fault. Some weak spots develop slowly, with a high frequency and intensity of partial discharges, while other weak spots develop suddenly. Most weak spot seem to be discharging at a low level, before developing high intensity, high frequency discharges. In all the presented cases the network owner was warned in time by PD-OL to remove the weak spot before failure.

VI. CONCLUSIONS

PD-OL has many advantages over off-line PD measurement methods:

- Partial discharges are measured in optimal test conditions, i.e. in normal operating mode
- The cable can stay in-service during installation
- Continuous monitoring and trending of hourly PD data
- On-line TDR
- Automatic upload of PD data to interpretation database
- Specialist KEMA review of PD activity
- View PD activity from your desk
- Review the condition of more than a hundred cable systems in just one morning
- Increased overall safety for field personnel

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VIII. ACKNOWLEDGMENT

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IX. BIOGRAPHIES

André N. Cuppen (M'1979) was born in Amsterdam, the Netherlands, on December 13, 1979. He studied Electrical Engineering at the Eindhoven University of Technology (EUT). He was chairman of the board 2000-2001, and an active member of several committees of the IEEE Student Branch Eindhoven. He worked on at the CRC Mining group of the University of Newcastle, Australia. He received his B.Sc. degree in 2004, and his M.Sc. degree in 2005.

In Australia, Ir. Cuppen implemented a power cable diagnostics program. In 2009 André joined KEMA in the Netherlands as a specialist in the development team of the PD-online measurement system for power cables. He has a keen interest in insulation properties, diagnostics and remaining lifetime analysis of power cables and other power equipment.

E. Fred Steennis joined KEMA, Arnhem, The Netherlands, in 1982, after his education at the Technical University in Eindhoven, Eindhoven, The Netherlands, where he studied degradation mechanisms in energy cables for the Dutch utilities. It was on this subject that he received the doctor's thesis from the Technical University in Delft, Delft, The Netherlands, in 1989.

In and outside the Netherlands, he is a consultant on energy cables and is the author and a teacher of the KEMA course on Power Cables. At KEMA, he is currently senior consultant. Since 1999, he has also been a part-time Professor at the Technical University in Eindhoven, where he teaches and studies diagnostics for power cables.

Prof. Dr. Ir. Steennis received the Hidde Nijland award for his contributions in 1991. After that, his experience on degradation mechanisms and related test methods both in the field and the laboratory was further enhanced. Based on this expertise, he became the Dutch representative with the Cigré Study Committee on High-Voltage Cables. He is also a member of various international Working Groups.

Peter C. J. M. van der Wielen (M'93) was born in Hulst, the Netherlands, on March 6, 1973. He studied Electrical Engineering at the Eindhoven University of Technology (EUT), where he was also member of the board and many committees of the IEEE Student Branch Eindhoven. He received his M.Sc. degree in 2000. After that he started doing research on power cable diagnostics at both the Electrical Power Systems group at this university and KEMA, Transmission and Distribution Testing Services, in the Netherlands. In 2005 he received his Ph.D. degree for his study on on-line detection and location of PDs in medium voltage power cables. Since then he works as a consultant/specialist on power cables at KEMA. Subjects in the field of work are: power cable diagnostics, power cable consultancy in general, asset management, development of new measuring techniques & diagnostic methods and failure analysis. Furthermore, he is one of the lecturers of the KEMA Power Cable Courses.